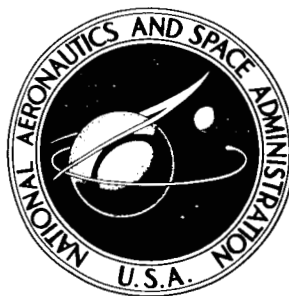


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SUMMARY

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Incipient cavitation of ethylene glycol was studied in a transparent Venturi mounted in a small closed-return hydrodynamic tunnel. Because previous research (NASA Technical Note D-2662) showed a variation of incipient-cavitation level with temperature, this glycol study was conducted over a temperature range of 76° to 126° F. For comparison, a parallel study using water at temperatures of 36° to 124° F was also conducted. The Venturi employed a modified quarter round (nominal rad., 0.183 in.) to provide a transition from a 1.743-inch-diameter approach section to a 1.377-inch-diameter throat. For ethylene glycol the incipient-cavitation parameter (ratio of the difference between an upstream reference pressure at incipient cavitation and vapor pressure to the velocity pressure of the upstream flow) increased about 26 percent as the approach velocities were increased from 19 to 46 feet per second. At incipient conditions, the minimum wall pressures were always significantly less than stream vapor pressure. The value of these effective liquid tensions for glycol varied from about 2 pounds per square inch at 16 feet per second to 13 pounds per square inch at 48 feet per second and were substantially independent of liquid temperature. The incipient-cavitation parameters for glycol were generally less than those for water but increased with increasing temperature. For water at less than 80° F, the cavitation parameter was substantially unaffected by temperature; above 80° F, the parameter decreased with increasing temperature. For temperatures less than 80° F, effective water tensions were practically independent of temperature but increased as much as 25 percent as temperature was increased to 120° F. Water tension values obtained at 120° F were about 15 percent less than those for ethylene glycol.

INTRODUCTION

AUTHOR →

Cavitation may be described as the formation and subsequent collapse of vapor cavities in a flowing liquid caused by pressure changes due to changes in flow velocity. The

first small, but visible, rupture of the liquid is usually defined as incipient cavitation. At or just prior to incipient conditions, the flowing liquid generally experiences a state of superheat locally (local pressures less than vapor pressure), and thus, the liquid is effectively in a state of tension (refs. 1 to 5). Experimental cavitation studies employing water, liquid nitrogen, and Freon-114 (dichlorotetrafluoroethane) in the identical Venturi (refs. 1 to 3) showed that values of liquid tension, and consequently, the incipient-cavitation level, differed significantly for the three liquids. Although the role of nuclei in the incipient-cavitation process is not clearly understood (ref. 5), it appears that pure fluid properties in themselves are strongly involved in the cavitation process. The study employing Freon-114 (ref. 3) showed that a modest change in liquid temperature alone had an appreciable effect on the incipient-cavitation level. At present, however, the manner in which particular fluid properties influence cavitation is not apparent; thus, to obtain a better understanding of fluid property effects, further studies using various liquids, temperature levels, and model shapes are required.

The purpose of this investigation was to study the incipient-cavitation characteristics of ethylene glycol as affected by flow velocity and liquid temperature in the same Venturi used for other liquids (refs. 1 to 3) and to compare these results with those obtained from a parallel study with distilled water. This latter phase of study extended previously obtained cavitation data for water in the same model (ref. 1) to include effects of liquid temperature. The choice of ethylene glycol as a test fluid was made primarily on the basis of its high viscosity (absolute viscosity about 18 times that for water at 80° F). The study was conducted at the NASA Lewis Research Center as part of a general program of cavitation research. The Venturi (1.377-in. -diam. throat) was mounted in a small closed-return hydrodynamic tunnel submerged in an antifreeze solution (for temperature control). For the glycol studies, flow velocities in the Venturi approach section were varied from 16 to 47 feet per second at controlled liquid temperatures from 76° to 126° F; the test ranges for water were 19 to 53 feet per second and 36° to 124° F. The ranges of flow velocities and maximum temperatures studied were governed by the limitations of the facility.

APPARATUS

Except for minor differences discussed herein, the facility used in the present study is identical to that described in detail in references 1 (tunnel portion only) and 2 (complete facility). Briefly, the facility consists of a small closed-return hydrodynamic tunnel (capacity, ~10 U.S. gal) designed to handle various liquids including cryogenic liquids. The tunnel will accommodate 12-inch-long test sections with a maximum inlet diameter of 1.743 inches. The facility incorporates a liquid bath surrounding the tunnel that serves

as a heat sink (particularly for operation with cryogenic liquids) and as a means for controlling tunnel liquid temperature. Temperature was controlled by a slowly circulated bath mixture of 60 percent ethylene glycol and 40 percent water. Temperature was varied by passing steam (5 lb/sq in. gage) or cold nitrogen gas through a sump-mounted single-tube heat exchanger.

The tunnel expansion, or pressurization, chamber used previously (refs. 1 and 2) was replaced by an accumulator containing a butyl rubber diaphragm in an effort to eliminate any free surface between the tunnel liquid and the tunnel pressurization gas. Because fine particles (presumably pump seal material) had been occasionally observed in the tunnel liquid in previous operations, a 10-micron filter was added to the tunnel loop for the present investigation. A small portion of the tunnel liquid was continuously passed through the filter from the high-pressure region of the pump to a lower pressure region downstream from the test section.

This present study using ethylene glycol and water was made with the same transparent-plastic Venturi section as that used for previous studies employing various liquids (refs. 1 to 3). The Venturi (fig. 1) contains a slightly modified quarter round (nominal radius, 0.183 in.), which provides a transition from a 1.743-inch-diameter approach section to a 1.377-inch-diameter throat. The 0.75-inch-long, constant-diameter throat is followed by a conical diffuser. The precise contour of the modified quarter round is presented in reference 2.

Tunnel and test-section pressures were measured by means of mercury manometers and calibrated bleed-type precision gages (accuracy, ± 0.15 lb/sq in.). Absolute values of tunnel liquid temperature were measured by means of a calibrated copper-constantan thermocouple mounted on the tunnel centerline approximately 14.5 inches upstream from

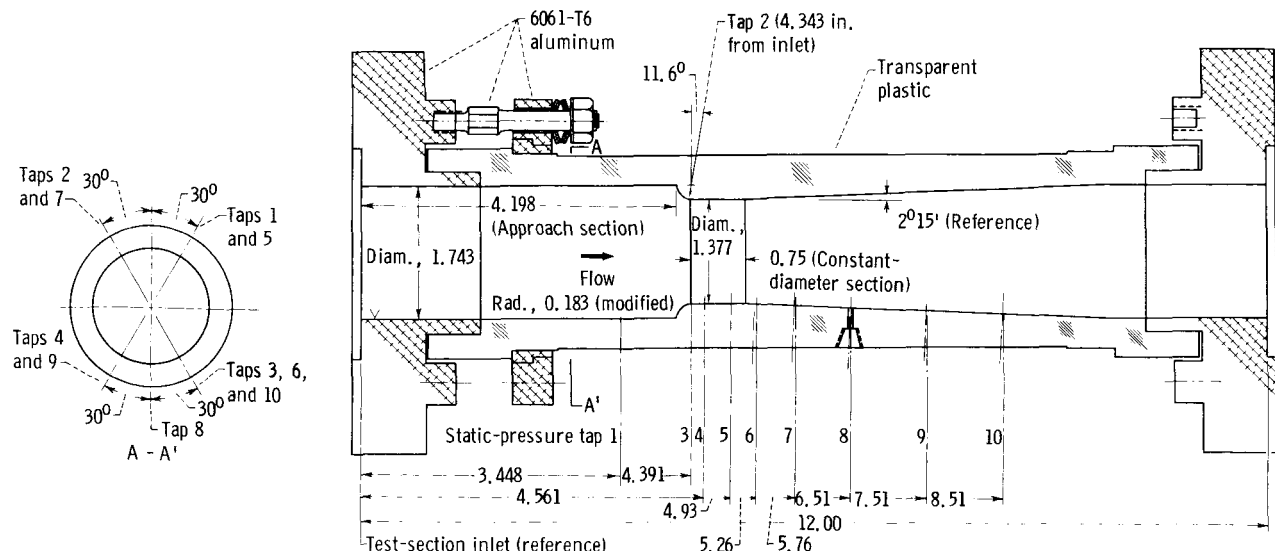


Figure 1. - Sketch of hydrodynamic Venturi section showing dimensions and pressure instrumentation. (Dimensions in inches.)

TABLE I. - PROPERTIES OF LIQUID ETHYLENE GLYCOL

Temperature, °F	Vapor pressure, ft of liquid abs.	Specific weight, lb/cu ft	Absolute viscosity, lb-sec/sq ft	Surface tension, lb/ft
40	4.9×10^{-4}	70.20	945×10^{-6}	34.12×10^{-4}
50	7.6	69.94	710	33.78
60	13.3	69.71	536	33.43
70	24.4	69.46	425	33.10
80	42.5	69.22	331	32.75
90	69.5	68.97	265	32.41
100	107	68.73	214	32.08
110	163	68.48	176	31.74
120	245	68.24	150	31.41
130	363	68.00	127	31.08
140	530	67.73	108	30.74

the test-section inlet. The appearance of cavitation was photographed by means of a 4-by 5-inch still camera in conjunction with a 0.5-microsecond, high-intensity flash unit.

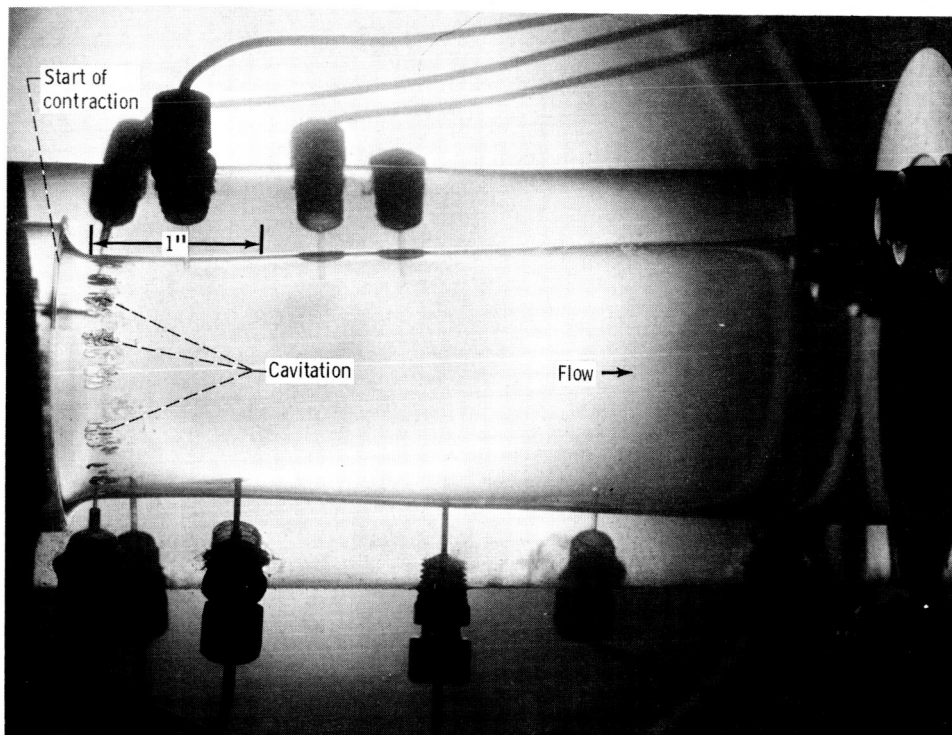
PROCEDURE

Conditioning of Liquids and Operating Techniques

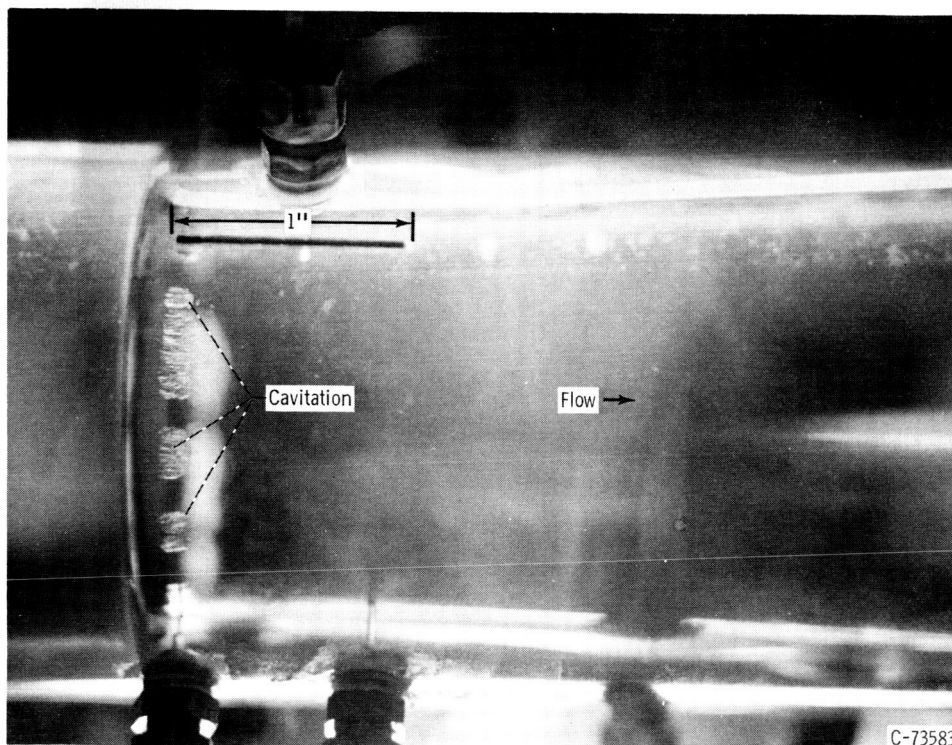
Commercial ethylene glycol of technical grade (clear, colorless, and free from inhibiting agents) was used in the present study. Some pertinent liquid properties for ethylene glycol (from ref. 6) are presented for convenience in table I. Because previous studies (ref. 1) showed no effect of water type on incipient cavitation for the present Venturi, triple-distilled water (from a ready supply at Lewis Research Center) was used in the water tests for convenience. Only one charge of each tunnel liquid was investigated.

Because both test liquids (as received) contained excessive amounts of gas (assumed to be air), the liquids were degassed by boiling in a clean processing tank (as in ref. 1) prior to tunnel use. To minimize contamination by air, the liquids were transferred to the tunnel by a vacuum technique (see ref. 1). No air was admitted to the processing tank during liquid transfer.

A conventional Van Slyke gas analyzer (see ref. 7) was used to determine air content. For ethylene glycol, the absolute air content was 1.8 parts per million (mg of air/kg of liquid). Results from several different bench tests showed that the air-saturation value for the particular glycol used herein is approximately 40 parts per million at a temperature of 70° F and atmospheric pressure. The absolute air content for water was



(a) Ethylene glycol. Free-stream velocity, 44.7 feet per second; free-stream temperature, 97.7° F.



(b) Water. Free-stream velocity, 44.3 feet per second; free-stream temperature, 103° F.

Figure 2. - Appearance of cavitation of ethylene glycol and water at near-incipient conditions.

2 parts per million, atmospheric saturation being about 23.5 parts per million at 70° F. Air content for each liquid remained constant throughout the study.

The cavitation induced on the walls of the Venturi was controlled by varying the overall tunnel pressure (pressurization or evacuation of the ullage space in the expansion chamber) at a fixed flow velocity and constant temperature (within $\pm 1^\circ$ F) in the Venturi approach section.

Incipient-Cavitation Criteria

The operating condition at which the formation and collapse of vaporous cavities near the model surface was just detectable by eye is defined herein as incipient cavitation. At this condition, the free-stream static pressure h_0 , free-stream velocity V_0 , and liquid temperature (to obtain vapor pressure h_v) were measured for subsequent determination of the incipient-cavitation parameter $K_i = (h_0 - h_v)/(V_0^2/2g)$. (Symbols are defined in the appendix.) Free-stream conditions refer to conditions existing in the approach section about 0.75 inch upstream from the quarter round. In general, the occurrence of incipient cavitation in glycol was similar to that occurring in water (fig. 2), the only noticeable difference occurring at the lower velocities and temperatures where the cavities in glycol tended to be larger and fewer in number. The conditions corresponding to the representative photographs of figure 2 are comparable but, for illustrative purposes, are slightly in excess of the incipient level. For both liquids, incipient cavitation was always evidenced by intermittent bursts of vapor cavities (1/8-in.-long minimum) with leading edges in the region of minimum pressure on the quarter round. These intermittent bursts occurred in a random manner about the periphery of the Venturi, and each burst usually lasted but a short time (order of msec). With increasing flow velocity, cavitation bursts were generally smaller, more numerous, and occurred with greater frequency.

No evidence of hysteresis was noted; that is, no measurable differences in incipient conditions were observed, whether the incipient state was approached from initially non-cavitating flow by decreasing pressure (onset method) or by increasing pressure from an initially cavitating state (suppression method).

Pressure Distribution

A typical wall pressure distribution for the quarter-round region of the Venturi is presented in figure 3(a). The conventional pressure coefficient C_p is plotted for various axial locations x/D . The data presented are from previous aerodynamic studies

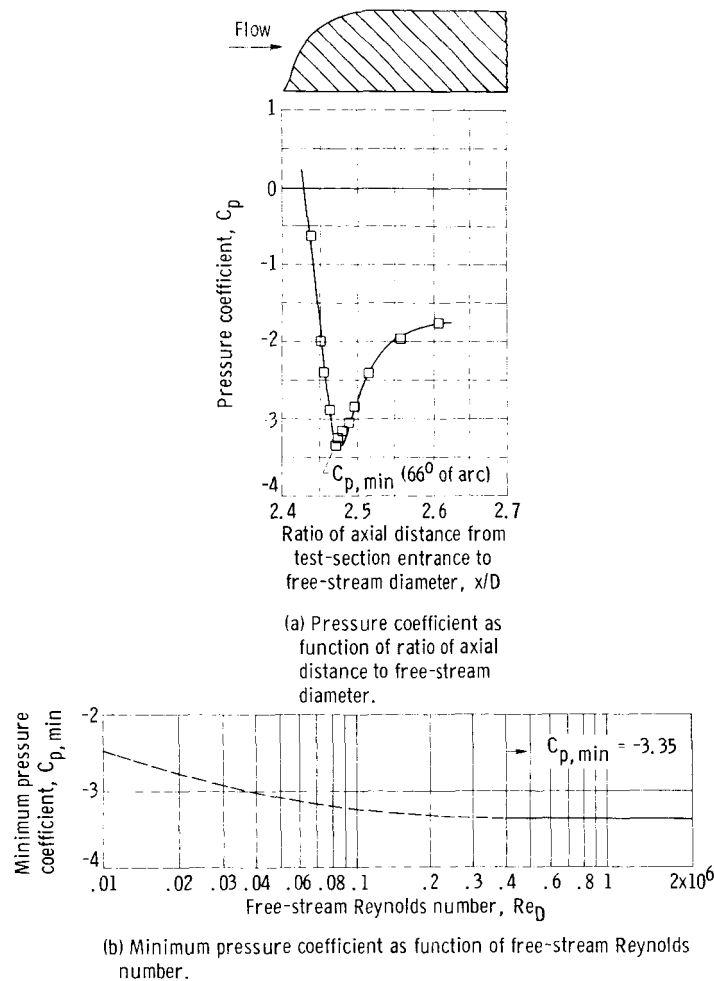


Figure 3. - Noncavitating pressure distribution and variation of minimum pressure coefficient with free-stream Reynolds number. Aerodynamic data from reference 3 for Reynolds numbers greater than 0.4×10^6 .

using an accurately scaled (4.61 scale) wind tunnel model of the present Venturi (see ref. 1). The aerodynamic results shown were corrected for compressibility (see ref. 3) and represent the fixed C_p profile obtained for $Re_D > \sim 0.4 \times 10^6$. From these aerodynamic results, it was determined that the minimum pressure coefficient $C_{p,min}$ was located at $x/D = 2.471$ (66° of arc) and had a value of -3.35. For $Re_D < 0.4 \times 10^6$, the pressure distribution data available for water ($0.2 \times 10^6 < Re_D < 0.7 \times 10^6$) and ethylene glycol ($0.01 \times 10^6 < Re_D < 0.1 \times 10^6$) indicated that C_p values continually became less negative with decreasing Re_D . The variation of $C_{p,min}$ with Re_D is presented in figure 3(b) and was determined as follows: Values of $C_{p,min}$ for $Re_D < 0.4 \times 10^6$ could not be measured directly because (1) reliable aerodynamic data could not be obtained for such low values of Re_D and (2) the small hydrodynamic Venturi did not include a pressure tap at the point of minimum pressure. The glycol C_p data ($0.01 \times 10^6 < Re_D < 0.1 \times 10^6$)

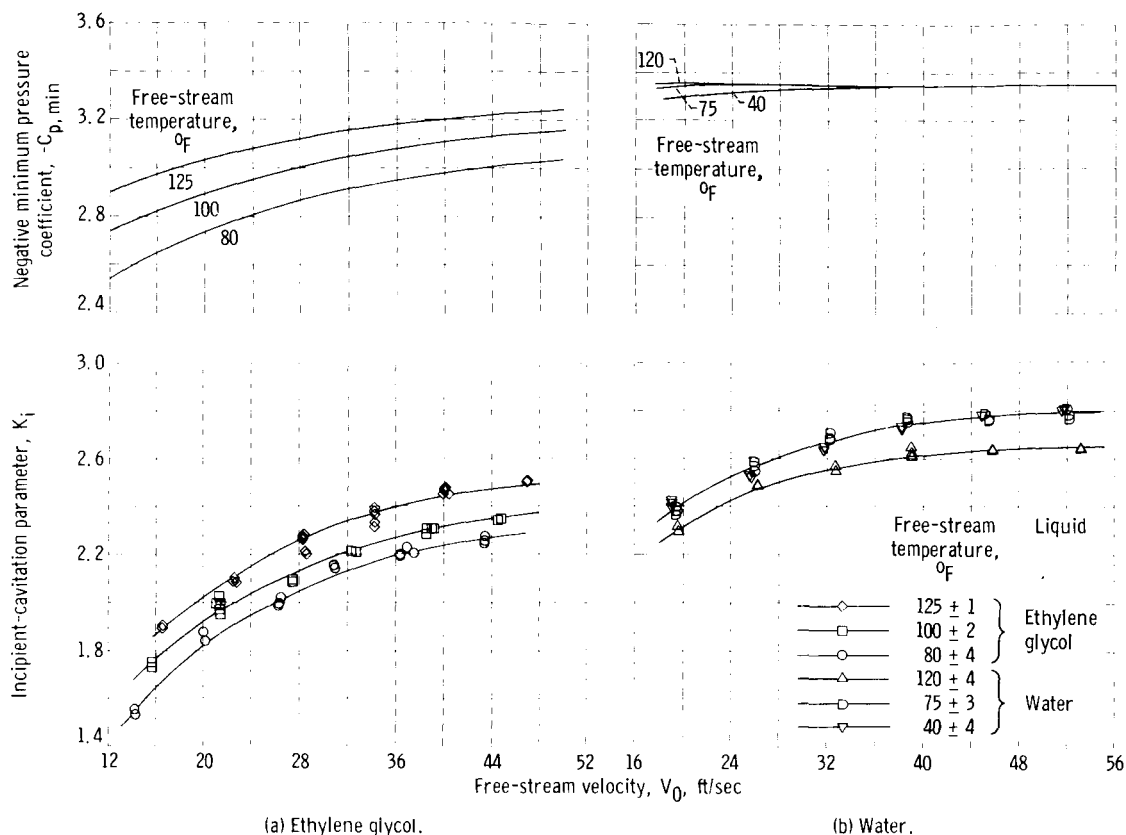


Figure 4. - Incipient-cavitation parameter and negative minimum pressure coefficient as functions of free-stream velocity and liquid temperature.

at the available tap locations (fig. 1, p. 3) were therefore extrapolated, at constant Re_D , to the $C_{p, \min}$ location. This extrapolation, although not conclusive in itself as to the absolute value of $C_{p, \min}$, established the trend of $C_{p, \min}$ with Re_D for $0.01 \times 10^6 < Re_D < 0.1 \times 10^6$. With this trend established, the glycol data (extrapolated to the $C_{p, \min}$ location) were then faired with a smooth curve to the constant value of -3.35 obtained from the aerodynamic studies at $Re_D > 0.4 \times 10^6$.

RESULTS AND DISCUSSION

The incipient-cavitation parameter K_i for ethylene glycol is presented in figure 4(a) as a function of free-stream velocity for nominal liquid temperatures of 80 $^{\circ}$, 100 $^{\circ}$, and 125 $^{\circ}$ F. The negative noncavitating values of $C_{p, \min}$ are included in the figure for convenient reference. For comparison, the water results obtained for nominal liquid temperatures of 40 $^{\circ}$, 75 $^{\circ}$, and 120 $^{\circ}$ F at flow conditions similar to those for glycol are presented in figure 4(b). For both ethylene glycol and water, the K_i values increased steadily with increasing flow velocity, becoming increasingly more parallel to the

$-C_{p, \min}$ curve at the higher velocities. As flow velocity was increased from 19 to 46 feet per second, the average increase in K_i was about 26 and 17 percent for glycol and water, respectively. For a given flow velocity, an increase in glycol temperature from 80° to 125° F produced about a 10-percent increase in the value of K_i . Because of the large variation in $C_{p, \min}$ over the range of Re_D included in the glycol study (0.014×10^6 to 0.1×10^6), however, the value of $-C_{p, \min}$ also increased with increasing temperature (about the same as K_i). The absolute values of K_i obtained in glycol were generally less than those for water. For water (fig. 4(b)) at a fixed flow velocity, inconsequential changes in the value of K_i were noted at temperatures less than approximately 80° F; above 80° F, the K_i values decreased with increasing temperature. From preliminary tests in which liquid temperature was steadily varied, the first measureable change in K_i was noted at temperatures slightly above 80° F. In a previous water study using the same Venturi (ref. 1), tunnel liquid temperature was not controlled, and therefore, the liquid temperature increased generally with increasing flow velocity (from about 79° F at 20 ft/sec to 100° F at 47 ft/sec). A comparison of the present water data obtained at constant temperature with that of reference 1 shows good agreement.

The incipient-cavitation results presented in figure 4 show that, for both liquids, K_i values were always appreciably less than $-C_{p, \min}$, which indicated that the minimum

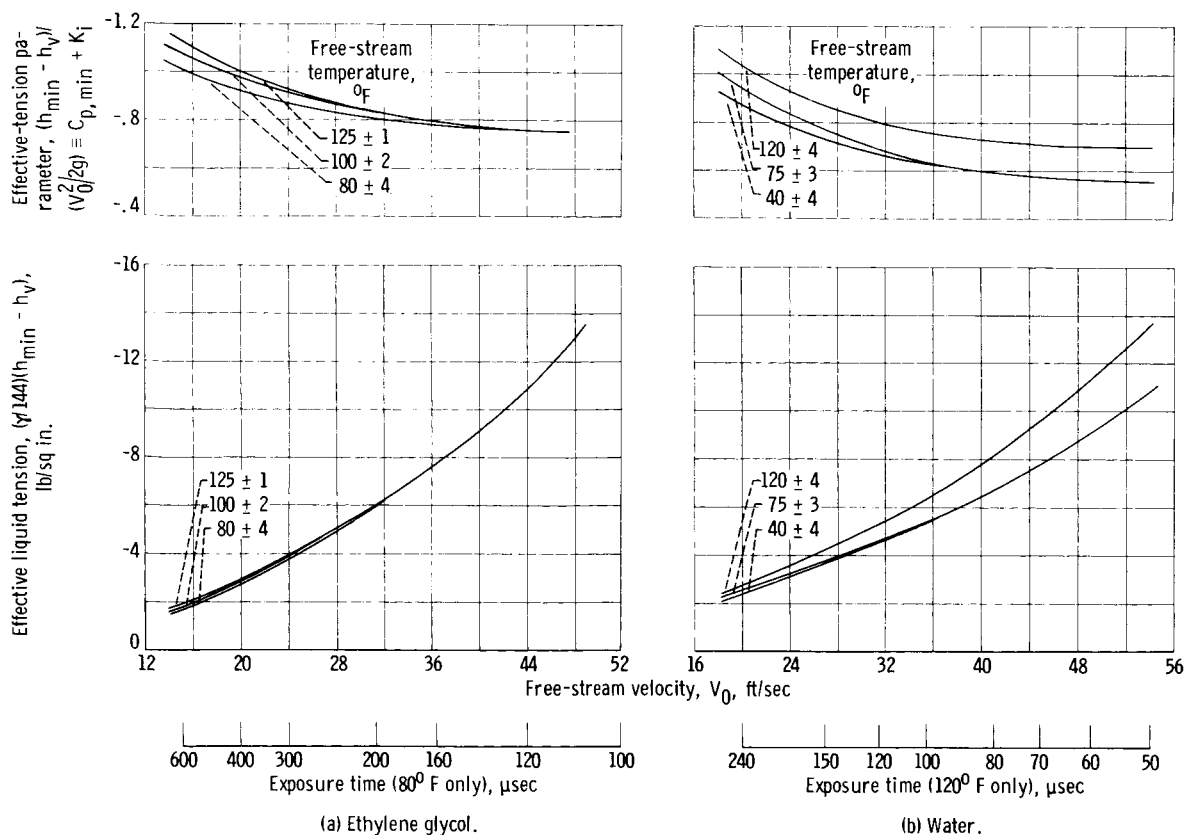


Figure 5. - Effective liquid tension based on incipient cavitation.

pressure h_{\min} on the model was always less than the free-stream vapor pressure h_v at incipient conditions. This difference between K_i and $-C_{p, \min}$ is a measure of the maximum decrement of pressure below stream vapor pressure (effective liquid tension) in terms of the velocity head $V_0^2/2g$. As in reference 2, the negative of this difference, that is, $K_i + C_{p, \min}$, is called the effective-tension parameter.

The faired glycol and water data of figure 4 are presented in figure 5 in terms of both the effective-tension parameter and the value of effective liquid tension in pounds per square inch. The effective-tension-parameter curves for both liquids are similar. At fixed temperature, the tension parameter became less negative with increasing velocity and approached a constant value at the higher velocities. For a fixed velocity, the tension parameter also tended to become less negative with decreasing temperature. The effective tensions (in lb/sq in.) for glycol increased rapidly with increasing flow velocity and were practically independent of temperature level for the range studied. Effective tensions ranged from about 2 pounds per square inch at 16 feet per second to 13 pounds per square inch at 48 feet per second. For water in the 40° to 80° F range, effective liquid tension was practically independent of temperature but increased appreciably (about 10 to 25 percent) as the temperature was increased to 120° F. Effective tensions for water at 120° F were about 15 percent less than those for glycol.

As the liquids flowed through the region of minimum pressure (pressure distribution of fig. 3), they experienced a range of tensions or pressure decrements relative to vapor pressure that varied from zero (when K_i and C_p were first equal) to the maximum values presented in figure 5 and back to zero again. The total time that a liquid is exposed to these pressures less than vapor pressure is herein called exposure time. Auxiliary scales showing calculated values of exposure time for ethylene glycol at 80° F and water at 120° F are presented for convenient reference at the bottom of figure 5. (The method for calculation is presented in ref. 1.)

The incipient-cavitation results of figure 4 are presented in figure 6 as a function of free-stream Reynolds number based on liquid properties corresponding to free-stream temperature. Results from the cavitation studies using Freon-114 (ref. 3) are included for comparison. The use of Re_D is merely for convenience in presenting the data ($-C_{p, \min}$ as a single curve against Re_D) and is not intended to demonstrate its usefulness as a correlating parameter. The use of approach diameter D as the characteristic dimension in Re_D bears no particular significance because it does not reflect the mechanisms involved in the cavitation process. The K_i values for the various liquids increased steadily with increasing Re_D and exhibited the same trends with respect to liquid temperature effects; that is, for a given value of Re_D (within the range studied for each liquid), the K_i values decreased with increasing temperature.

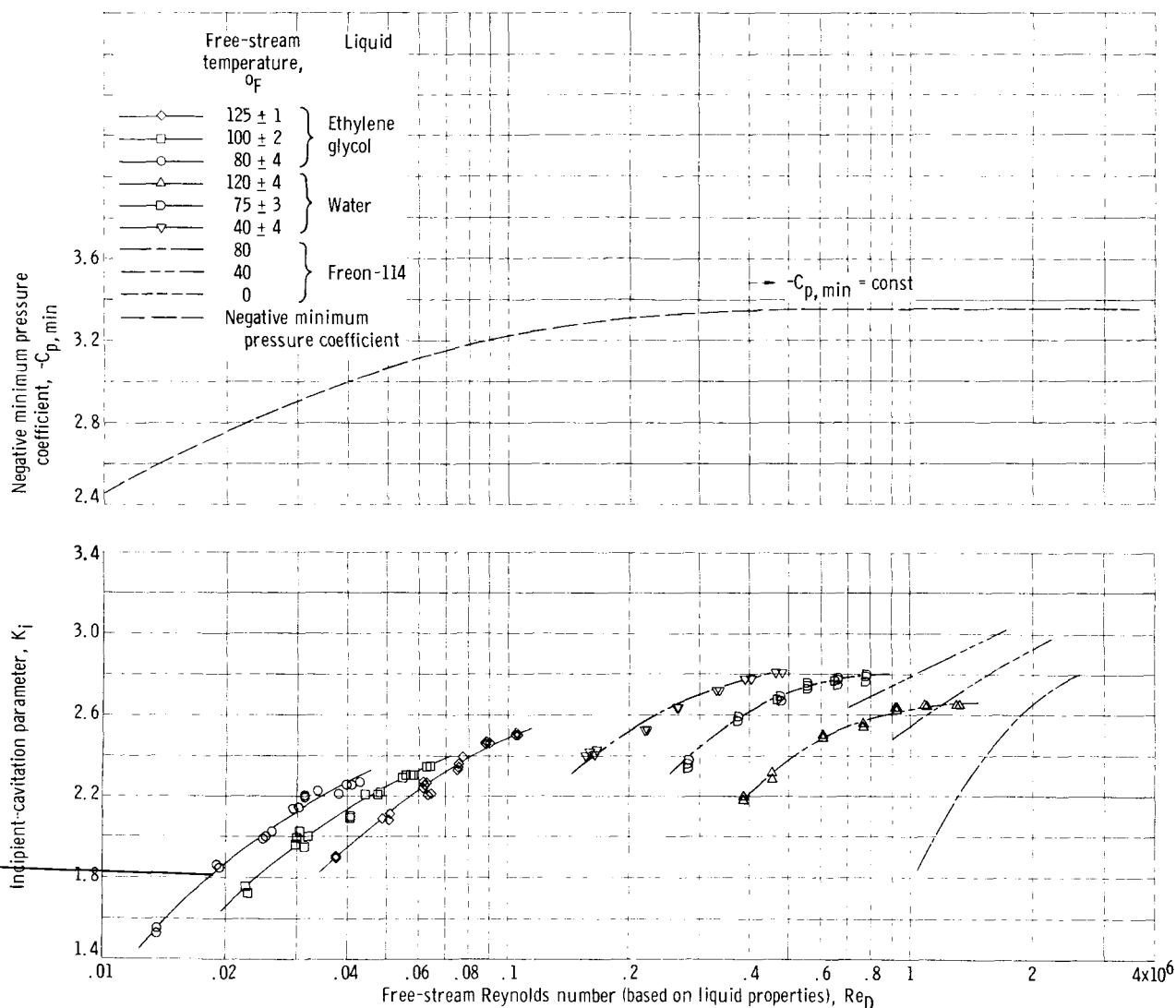


Figure 6. - Incipient-cavitation parameter and minimum pressure coefficient as functions of free-stream Reynolds number and liquid temperature.

SUMMARY OF RESULTS

Experimental incipient-cavitation studies with ethylene glycol and water over a range of flow velocities and liquid temperatures in a tunnel-mounted Venturi yielded the following principal results:

1. The incipient-cavitation parameter K_i for glycol increased about 26 percent as the free-stream velocity was increased from 19 to 46 feet per second. For a fixed velocity, the value of K_i also increased with increasing temperature, averaging about a 10-percent increase for a change in temperature from 80° to 125° F. Measured K_i values indicated that the minimum wall pressures at incipient conditions were always less

than stream vapor pressure. These effective liquid tensions for glycol ranged from about 2 pounds per square inch at 16 feet per second to 13 pounds per square inch at 48 feet per second and were substantially independent of liquid temperature.

2. The incipient-cavitation parameter for water increased with increasing flow velocity but was substantially unaffected by liquid temperature in the 36° to 80° F range. Above 80° F, K_i decreased with increasing temperature. Effective tensions in water were practically unaffected for temperatures less than 80° F, but increased as much as 25 percent as the temperature was increased to 120° F. For water at 120° F, tension values (in lb/sq in.) were about 15 percent less than those for glycol.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 30, 1964.

APPENDIX - SYMBOLS

C_p	noncavitating pressure coefficient, $(h_x - h_0)/(V_0^2/2g)$
$C_{p, \min}$	noncavitating minimum-pressure coefficient, $(h_{\min} - h_0)/(V_0^2/2g)$
D	free-stream diameter (1.743 for hydrodynamic model and 8.03 for aerodynamic model), in.
g	acceleration due to gravity, ft/sec ²
h_{\min}	minimum static pressure, ft of liquid abs
h_v	vapor pressure corresponding to free-stream liquid temperature, ft of liquid abs
h_x	static pressure at x/D , ft of liquid abs
h_0	free-stream static pressure at $x/D = 1.98$, ft of liquid abs
K_i	incipient-cavitation parameter, $[(h_0 - h_v)/(V_0^2/2g)]_{\text{incipient}}$
Re_D	free-stream Reynolds number based on diameter D
V_0	free-stream velocity at $x/D = 1.98$, ft/sec
x	axial distance from test-section inlet (see fig. 1), in.
γ	specific weight of liquid, lb/cu ft

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